Optical Hybrid Enables Next-Generation Optical Communication

Introduction

Since the late 1990s, the transport capacities of ultra-long haul and long-haul fiber-optic communication systems have been significantly increased by the introduction of EDFA, DWDM, dispersion compensation, and FEC technologies. For fiber-optic communication systems utilizing such technologies, the universal on/off-keying (OOK) modulation format in conjunction with direct detection methods have been sufficient to address data rates up to 10 Gb/s per channel.

In order to economically extend the reach and data capacity beyond such legacy systems and into next-generation networks, several technological advancements must take place, including but not limited to, 1) adoption of a differential phase-shift keying (DPSK) modulation format, as opposed to OOK; 2) developments in optical coherent detection; and 3) progress in adaptive electrical equalization technology. In combination, these technologies will boost a signal's robustness and spectral efficiency against noise and transmission impairments.

Such crucial strides in optical signal technology are no longer theoretical possibilities but are feasible solutions in present-day optical networking technology. The path for an optical coherent system has already been paved by 1) the deployment of DPSK modulated systems by Tier-1 network providers; and 2) the increased computational capacity and speed of electronic DSP circuits in receivers, which provides an efficient adaptive electrical equalization solution to the costly and difficult optical phase-lock loop. These advances coupled with Optoplex's introduction of a commercially feasible six-port optical hybrid solution should give pause to Tier-1 providers and carriers to reassess their earlier rationales for not adopting and implementing an optical coherent detection scheme. Perhaps with such advances, optical networks will begin to realize the benefits already recognized in microwave and RF transmission systems for extending capacity and repeaterless transmission distances through coherent detection.

Coherent Detection Advantages

- Higher receiver sensitivity
- Compatible with PSK modulation
- More tolerant to impairment
- Lower channel crosstalk
- Secure communication

Optical Coherent Systems

The commercial feasibility of a coherent system for optical signal transmission was first investigated around 1990 as a means to improve a receiver's sensitivity. In contrast to existing optical direct-detection system technology, an optical coherent detection scheme would detect not only an optical signal's amplitude but phase and polarization as well. With an optical coherent detection system's increased detection capability and spectral efficiency, more data can be transmitted within the same optical bandwidth. More over, because coherent detection allows an optical signal's phase and polarization to be detected and therefore measured and processed, transmission impairments which previously presented challenges to accurate data reception, can, in theory, be mitigated electronically when an optical signal is converted into the electronic domain.

However, the technology never gained commercial traction because the implementation and benefits of an optical coherent system could not be realized by existing systems and technologies.

Implementing a coherent detection system in optical networks requires 1) a method to stabilize frequency difference between a transmitter and receiver within close tolerances; 2) the capability to minimize or mitigate frequency chirp or other signal inhibiting noise; and 3) an availability of an "optical mixer" to properly combine the signal and the local amplifying light source or local oscillator (LO). These technologies were not available in the 1990s. A further setback to the adoption and commercialization of an optical coherent system was the introduction of the EDFA, an alternative low cost solution to the sensitivity issue.

Notwithstanding the myriad challenges, an optical coherent system (also referred to as "Coherent Light Wave") remains a holy grail of sorts to the optical community because of its advantages over traditional detection technologies:

- An increase of receiver sensitivity by 15 to 20 dB compared to incoherent systems, therefore, permitting longer transmission distances (up to an additional 100 km near 1.55 µm in fiber). This enhancement is particularly significant for space based laser communications where a fiber-based solution similar to the EDFA is not available.
- Compatibility with complex modulation formats such as DPSK or DQPSK.
- Concurrent detection of a light signal's amplitude, phase and polarization allowing more detailed information to be conveyed and extracted, thereby increasing tolerance to network impairments, such as chromatic dispersion, and improving system performance.
- Better rejection of interference from adjacent channels in DWDM systems, allowing more channels to be packed within the transmission band.
- Linear transformation of a received optical signal to an electrical signal that can then be analyzed using modern DSP technology.
- Suitable for secured communications.

There is a growing economic and technical rationale for adoption of a coherent optical system now. Academic and industrial research results have demonstrated that coherent optical systems are feasible today using advanced but commercially available optical components. The six-port 90° optical hybrid device developed by Optoplex is based on such practical requirements.

Six-Port Optical Hybrid

Six-port hybrid devices have been used for microwave and millimetre-wave detection systems since the mid-1990s and are a key component for coherent receivers. In principle, the six-port device consists of linear dividers and combiners interconnected in such a way that four different vectorial additions of a reference signal (LO) and the signal to be detected are obtained. The levels of the four output signals are detected by balanced receivers. By applying suitable baseband signal processing algorithms, the amplitude and phase of the unknown signal can be determined.

For optical coherent detection, the six-port 90° optical hybrid would mix the incoming signal with the four quadratural states associated with the reference signal in the complex-field space. The optical hybrid would then deliver the four light signals to two pairs of balanced detectors. *See Fig. 1 for block diagram of a coherent receiver.*

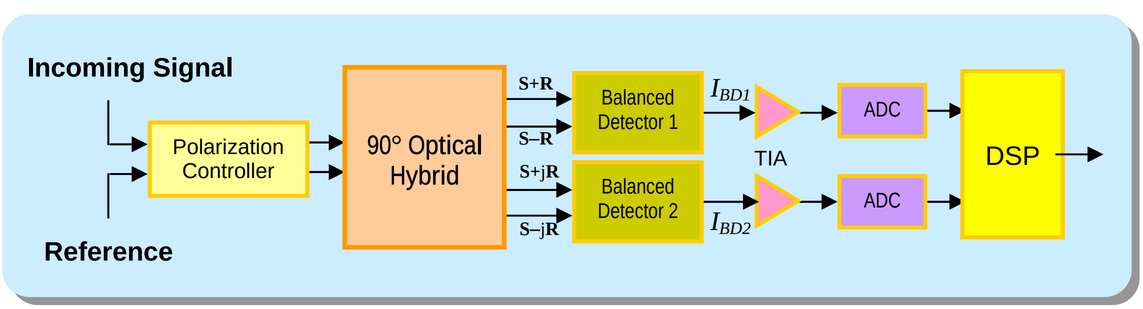

Figure 1. Schematic diagram of optical coherent receiver.

Let $\mathbf{S}(t)$ and $\mathbf{R}$ denote the two inputs to the optical hybrid and $\mathbf{S}(t)+\mathbf{R}\exp[j(\frac{\pi}{2}n)]$, with $n = 0, 1, 2$ and 3, represent the four outputs from it. Using the PSK modulation and phase-diversity homodyne receiver as an illustration, one can write the following expression for the signal power to be received by the four detectors:

$$P_n(t) \propto P_S + P_R + 2\sqrt{P_S P_R}\cos[\theta_S(t) + \theta_C(t) - \frac{\pi}{2}n],\ n = 0, \ldots 3;$$

where P_S and P_R are the signal and reference power, respectively, $\theta_S(t)$ the signal phase modulation, and $\theta_C(t)$ the carrier phase relative to the LO phase. With proper subtractions, the two photocurrents fed to the TIA's can be expressed as

$$I_{BD1} \propto \sqrt{P_S P_R}\cos[\theta_S(t) + \theta_C(t)];$$

$$I_{BD2} \propto \sqrt{P_S P_R}\sin[\theta_S(t) + \theta_C(t)];$$

encompassing the amplitude and phase information of the optical signal. Accordingly, the average electrical signal power is amplified by a factor of $4P_R/P_S$. Following this linear transformation the signals are electronically filtered, amplified, digitized and then processed. Compared to a two-port optical hybrid, the additional two outputs have eliminated the intensity fluctuation from the reference source (LO).

An optical coherent receiver requires that the polarization state of the signal and reference beam be the same. This is not a gating item as various schemes or equipment are available to decompose and control the polarization state of the beams before they enter the optical hybrid. Further, certain polarization controllers can be used to provide additional security functionality for optical coherent systems, preventing third parties from tapping information or data streams by implementing polarization scrambling and coding techniques.

90° Optical Hybrid Features

- Two inputs for signal and LO
- Four outputs mixing signal and LO
- Deliver both amplitude and phase of signal
- Amplify signal linearly
- Suitable for both homodyne and heterodyne detection

Implementation of Optical Hybrid

For laboratory purposes, the 90° optical hybrid has traditionally been constructed using two 50/50-beam splitters and two beam combiners, plus one 90° phase shifter *(see Fig. 2)*. These optical hybrids can be implemented using all-fiber or planar waveguide technologies; however, both methods have their respective drawbacks. Both technologies require sophisticated temperature control circuits to sustain precise optical path-length difference in order to maintain an accurate optical phase at the outputs. In addition, fiber-based devices are inherently bulky and are unstable with respect to mechanical shock and vibration; whereas, waveguide-based products suffer from high insertion loss, high polarization dependence and manufacturing yield issues. Waveguide-based products are also not flexible for customization and require substantial capital resources to set up.

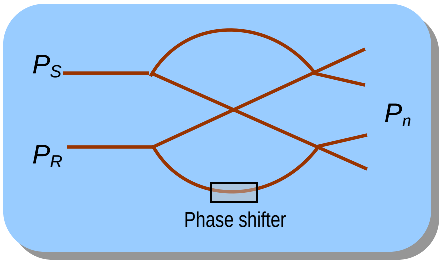

Figure 2. Fiber or waveguide implementation of optical hybrid.

Optoplex's Passive Optical Hybrid

Optoplex's patent-pending 90° optical hybrid is based on the Michelson interferometer principle. The Michelson interferometer principle has been proven and tested in free-space bulk-optics and optical component manufacturing. Free-space bulk-optics is a mature technology with a proven track record in providing many critical components, such as circulators, polarization beam combiners, wavelength lockers, dispersion compensators, interleavers and DPSK demodulators, to the fiber-optic communication industry. In addition, bulk-optics based devices have low insertion loss and their core optics can be readily coupled to commercially available fiber collimators.

The fundamental strength of the Michelson-interferometer design is that all beams share the same main optical element during most of their paths so that the phase relationship among the different outputs — a key performance parameter — will not be sensitive to temperature variation, mechanical shock and/or vibration.

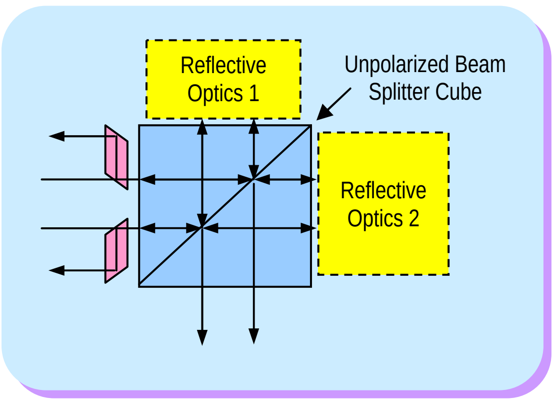

Figure 3. Illustrative optical layout for Optoplex's optical hybrid device.

Michelson-Interferometer Based Optical Hybrid Advantages

- Compact
- Passive (No temperature control)
- Polarization independent
- Environment insensitive (athermal)
- Mature technology
- Precise phase control
- C+L band coverage by a single device
- Integratable with polarization controller

Optoplex's design for its passive optical hybrid incorporates the same core optical platform, collimating and hermetic packaging technology shared by Optoplex's passive, athermal interleaver and DPSK demodulator. These products have gone through rigorous Telcordia testing and benefit from years of manufacturing experience.

Free from any active control, Optoplex's optical hybrid is compact (less than 40 x 40 x 14 mm), polarization-independent, and thermally stable. *See Fig. 3 for a schematic diagram of a standard optical design layout.* The table below lists the achievable specifications for several key parameters of Optoplex's optical hybrid.

Parameter	Unit	Specification
Wavelength Range (C+L Band)	nm	1527 ~ 1607
Phase Difference	deg	90±5
Excess Insertion Loss (any input to any output)	dB	<2.0
Insertion Loss Difference (between any two conjugate outputs)	dB	<0.5
Optical Return Loss	dB	>30

Optoplex's Michelson-interferometer based optical hybrid can also be integrated with the polarization controller, a required component for an optical coherent receiver *(see Fig. 1)*. By integrating the optical hybrid and polarization controller into one device, a more cost-effective, compact and performance-enhanced component can be manufactured. In contrast, all-fiber or waveguide based devices cannot realize these same benefits because these technologies cannot be similarly combined.

The technological barriers against adopting and commercializing an optical coherent system have been overcome. First, stabilizing the frequency difference between a transmitter and receiver within close tolerances may be accomplished with current advancement in electronics; secondly, system designers have begun introducing the PSK modulation format in network systems, thereby eliminating the frequency chirp associated with OOK; and finally, with the introduction of Optoplex's optical hybrid, the final key component for mixing the signal and reference beam in the optical domain has become available.

These advancements in key technological fronts should create sufficient impetus for carriers to re-examine the benefits and economic rationale of an optical coherent system. With Optoplex's optical hybrid, the full advantages of a coherent detection scheme may be realized: higher receiver sensitivity, compatibility with PSK modulation, increased tolerance to transmission impairment, more channels within the available bandwidth, and secured communications. As coherent detection stirs renewed interests within the optical communication industry, a revolution may soon be coming. Optoplex stands ready with a product that many researchers and network system developers have long waited for.

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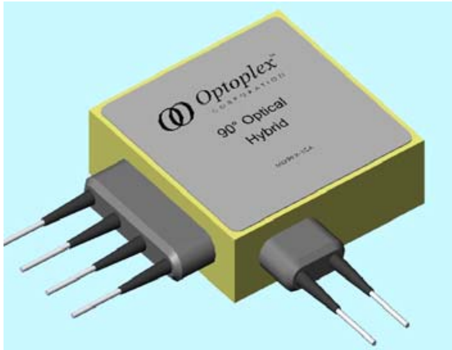

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